



## Unexpected Mesons $X, Y, Z, \dots$ (tetraquarks? hadron molecules? ...)

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### Abstract

This talk briefly discusses the set of meson resonances discovered in the latest decade. They are frequently treated in the literature as tetraquarks or hadron molecules. Our consideration (using the energy-time uncertainty relation) suggests, however, that the most reasonable description for each of them may be a two- (or more-) component Fock column, with one line being a conventional quark-antiquark pair, and the other line(s) corresponding to a charmed (or beauty) meson-antimeson pair near its threshold. Detailed investigation of decay properties might allow to reveal presence of several Fock components and separate their contributions.

**Keywords:** tetraquarks, charmed mesons, charmonium, threshold enhancements, Fock components

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### 1. Introduction. Reminder

One of the basic points of the Standard Model is the existence of quarks (and, of course, corresponding antiquarks) of 6 different kinds (flavors) with different masses: 3 quarks  $u, c, t$  having the electric charge  $+2/3$  and 3 quarks  $d, s, b$  with the charge  $-1/3$ . Further, it is widely accepted at present that every (at least well-studied) meson consists of one quark and one antiquark having, generally, different flavors. There is only one exception here: the heaviest  $t$ -quark is so short-living that it has not enough time to produce any hadrons.

Such a simple picture provides limitations for quantum numbers of both mesons and baryons. For instance, baryons can not have positive strangeness  $S$ , or isospin  $I$  higher than  $3/2$ ; mesons can not have  $I$  higher than 1, their  $S$  may be only  $0, \pm 1$ . Limitations arise also for  $J^{PC}$  values:  $q\bar{q}$  mesons can have, *e.g.*,  $J^{PC} = 0^{-+}$ , but can not have  $0^{+-}$ .

Note, however, that such a picture is inconsistent with any version of relativistic field theory, where one can not exclude presence of an arbitrary number of virtual quark-antiquark pairs and/or gluons. Therefore, adequate description of any hadron should use a Fock col-

umn, where lines correspond to particular configurations (but with the same “global” quantum numbers, like  $I, J, P, C$ , and so on).

When describing the lower hadron states by the constituent quark model, the model parameters and interaction potentials are usually chosen so that higher Fock components can be ignored, with some accuracy. It is not evident, however, whether the same approach, with the same parameters and potentials, may be applicable for excited states as well.

### 2. “Prehistoric” tetraquarks

Up to now, there have been found no mesons with “non-canonical” quantum numbers, which could not exist in a quark-antiquark system. Nevertheless, there is a tendency to explain any anomalous features of a meson resonance by presence, or even dominance, of tetraquark (*i.e.*, two quark-antiquark pairs) component(s) in its structure. As an alternate, one could consider hadron molecules, bound states of two (or more) hadrons. For the first time, such hypotheses were applied to the scalar mesons  $a_0(980)$  and  $f_0(980)$  (the cor-

responding story is briefly presented in the Introduction to Ref.[1]). Though the discussions are still continuing, the necessity of the tetraquark nature of the scalar mesons stays unproven (see, *e.g.*, Conclusions in Ref.[1]).

Later, the tetraquark configurations were searched for in excited  $D$ -mesons, such as  $D(2400)$  and heavier. The corresponding discussions still arise again and again, but any definite conclusion has not been reached yet, just as for the scalar mesons.

### 3. New era

New, and numerous, class of states appropriate to search for tetraquark configurations was revealed about ten years ago, initially in studies at  $B$ -factories. They are denoted by the symbols  $X, Y, Z$ . These states are mainly found in  $B$ -meson decays, but also as a part of cascades in the process  $e^+e^- \rightarrow \text{hadrons}$ . Their common property today is presence of the charmed  $c$ -quark pair among decay products. The charm may be hidden, as a charmonium state, or open, as a charmed meson pair (there have been found also several states with the  $b$ -quark pair in decay products).

The whole list of observed new states and their decay modes may be found in a number of reviews on this new spectroscopy (some of more recent talks and papers see, *e.g.*, in Ref.[2]). Even more papers and talks discuss the  $X, Y, Z$  studies at particular experimental facilities. All observed states of this group are included also in the Report of Particle Physics [3]. Note, however, that those states are usually seen as peaks in the mass spectra of decay products. Meanwhile, as known, peaks might arise not only due to resonance states, but also because of some kinematic effects. It is important in this respect, that the resonance character of the peak has been demonstrated for at least one of  $Z$  states,  $Z(4430)$ , by the energy dependence of the phase of the corresponding amplitude [4]. All other peaks  $X, Y, Z$  are only supposed today to be true resonances (see, however, more general theoretical arguments against pure kinematic effects in Ref.[5]).

But even if all those states were proved to be just resonances it would not mean that we understand their internal structure. Each of them might consist of a familiar quark-antiquark pair, or be a more complicated system. The most frequent pictures considered in the literature are tetra quarks, bound states consisting of two quarks and two antiquarks, or hadron molecules, bound states of two (or more) hadrons. Clear physical discrimination of these pictures is usually not discussed, but methods of calculation may be different. For instance, tetraquarks

are frequently described by sum rules, though various other approaches have been applied as well. Many publications pretend to give satisfactory description of a particular state, but nobody could present a picture of the  $X, Y, Z$  states as a whole. Thus, their theoretical status stays uncertain. Representative, in this respect, is the fate of Ref.[6]. Its first version was able to see one  $Z$  state, as a result of lattice calculations, while its second version sees no such states in the whole investigated region.

### 4. Mesons $X$ and $Y$

All known states of these kinds are neutral. Being tetraquarks (with one pair  $c\bar{c}$ ) or hadron molecule (of two charmed mesons), they could have isospin  $I = 0$  or 1. Decay modes do not give a definite answer. For instance,  $X(3872)$  can decay both to  $\rho^0 J/\psi$  (with  $I = 1$  in the final state) and to  $\omega J/\psi$  (with  $I = 0$ ), which means, of course, isospin violation in one of the channels. Were the  $X(3872)$  isovector, it should have a charged companion. However, despite intensive searches, no charged companions have been found for any of  $X, Y$  states. This favors  $I = 0$  (if so, isospin violating should be the decay to  $\rho^0 J/\psi$ ).

A meson with such quantum numbers and with charmed quark pair (open or hidden) in all decay modes could be just an excited state of charmonium. Indeed, the measured  $X, Y$  masses are close enough to calculated (alas, model-dependent) levels of charmonium. For one of such mesons,  $X(3915)$ , the Particle Data Group have even made their minds to identify it with a charmonium level,  $\chi_{c0}(2^3P_0)$  [3]. However, calculated (again, model-dependent) decay properties differ from the observed ones (for the particular case of  $X(3915)$ , see Ref.[7]). Thus, identification of  $X, Y$  mesons as charmonium levels stays questionable, though admissible.

### 5. Mesons $Z$

A harder problem is the nature of states  $Z$ . They have neither strangeness, nor charm, nor beauty, but all their decay modes, observed up to now, contain open or hidden charm (for  $Z_c$  states; there have been found also a couple of states  $Z_b$ , which decays produce open or hidden beauty; this makes the problem more general). However, all the  $Z$  states are charged and have isospin  $I = 1$  (for one of them,  $Z_c^\pm(3900)$ , the neutral component,  $Z_c^0(3900)$ , has been found as well [8]). Therefore, they definitely can not be charmonium (or bottomonium) levels. On the other hand, all the  $Z$  states

have rather large widths (typically, some tens of MeV or even more). Thus, their decays are governed by strong interactions, which conserve every flavor. Therefore, the final  $c$ - or  $b$ -quarks could not arise as a result of flavor changes in the decay (as could be in weak decays). On the other hand, pair production of heavy flavors should be suppressed, according to the Zweig-lizuka rule. These facts provide a hint of presence of the heavy quark pair just in the initial state. Were the hint true, the  $Z$  states would indeed be tetraquarks (e.g.,  $u\bar{d}c\bar{c}$ ) or hadron molecules with the same quark content. Such situation is believable, but is not proven yet and stays uncertain. In any case, nobody could achieve general description of the  $Z$  states along such lines.

## 6. Possible role of thresholds

In the space-time picture, higher Fock components are related to quantum fluctuations. When considering hadrons in QCD, those fluctuations may be described either as containing additional  $q\bar{q}$  pairs and/or gluons (compare to virtual photons and/or  $e^+e^-$  pairs in QED), or as two- or multihadron systems. The fluctuations arise and then disappear after some characteristic time. According to the well-known energy-time uncertainty relation, the lifetime of a fluctuation (in terms of virtual hadrons) is the shorter, the larger is difference between the initial state mass and physical mass of the virtual hadronic state.

If a hadron under consideration is a resonance state, it has itself some finite lifetime. Let us assume that the resonance has just a canonical quark-antiquark pair as the basic Fock component. Now, if a fluctuation develops a (virtual) hadron system with its physical mass far above the resonance mass, then the fluctuation has very short lifetime. It arises and disappears before the resonance decays. Of course, such fluctuation affects properties of the resonance, but only as a correction. If, just opposite, the resonance mass is far above the threshold of a hadron system in fluctuation, then the arising hadrons turn out to be real. They rapidly run away after the fluctuation has arisen. Sure, the resonance lifetime in such a case is mainly related not to the time of running away, but to the time (and probability) of producing the corresponding fluctuation.

These two extreme considerations show that thresholds may play a special important role. Indeed, if the fluctuation produces a hadron system in a limited mass range near its threshold, then the fluctuation lifetime may be near or even longer than the resonance lifetime. In such a case, when describing the resonance, one should consider the fluctuation as permanent. In other

words, a near-threshold fluctuation can not be averaged out, it becomes effectively enhanced and “stabilized”. The corresponding Fock column for the resonance can not be considered as one-component; even minimally, it should be two-component. Of course, presence of additional Fock components should be accounted for when calculating masses and decay properties of the resonances.

Phenomenologically, this situation arises if the resonance Breit-Wigner peak overlaps a threshold. To some extent, the case is similar to the known cusp effect, which provides enhancement of an elastic cross section in a narrow energy range near an inelastic threshold (discussion of the  $Z$ -states in respect with cusps may be found in Ref.[9]). Just as for cusps, the largest contributions to the higher Fock components should come from hadron pairs in the near-threshold  $S$ -wave state.

Among the “old” resonances, some cases seem to encounter just such threshold effects. They are, first of all, the scalar resonances  $f_0(980)$  and  $a_0(980)$ , mentioned above as “prehistoric” tetraquarks. Their masses and widths [3] are such that the Breit-Wigner peaks overlap the  $K\bar{K}$  threshold. Moreover, the resonance masses are so close to the kaon-pair threshold(s) that the resonance properties are affected by the difference of thresholds for the charged and neutral kaon pairs. This distorts isotopic relation between kaons and produces apparent isospin violation, thus generating the observable  $f_0$ - $a_0$  mixing.

The other interesting example is the hyperon resonance  $\Lambda(1520)$ . Its decay to  $\Sigma(1385)\pi$  has, formally, no energy release and, therefore, vanishing final-state phase space. At first sight, it should be kinematically forbidden or, at least, suppressed. However, the branching ratio for the mode  $\Lambda(1520) \rightarrow \Sigma(1385)\pi$  is unexpectedly large, about 10% [3]. It could be just a result of the threshold enhancement.

This discussion shows that higher Fock components can not be completely expelled. One may be able to construct a model and adjust its parameters so to describe the lowest hadron states (nearly) without higher components. But for excited states, those components, most probably, will occur non-negligible. Of course, such expectations are equally applicable to both mesons and baryons.

Note that the arising picture differs from the two approaches most popular in the literature. For instance, a meson with such structure is not a canonical tetraquark, since it contains a quark-antiquark component. Hence, it may have only quantum numbers which are admissible for the quark-antiquark pair; in terms of the  $SU(3)_F$ , it can belong only to the lowest multiplets. On the other

side, the hadron component of such a meson is not a bound molecule, it is dominated by the hadron near-threshold system.

## 7. New mesons as Fock columns

Let us apply the above viewpoint to the  $X(3872)$ , with mass 3871.7 MeV, width  $< 1.2$  MeV, and  $J^{PC} = 1^{++}$  [3]. We assume that its lowest component corresponds to  $c\bar{c}$  with  $I = 0$ . Then, it overlaps the threshold of  $D^0\bar{D}^{*0}$  (or  $D^{*0}\bar{D}^0$ ) at 3871.8 MeV, but not the threshold of  $D^+\bar{D}^{*-}$  (or  $D^-\bar{D}^{*+}$ ) at 3879.9 MeV [3]. Note that the  $X(3872)$ , because of its spin-parity, is not coupled to  $D\bar{D}$ . Thus, the corresponding Fock component can contain only neutral  $D$ -meson contribution (in terms of the quark content, it may be considered as the tetraquark configuration  $\bar{u}u\bar{c}c$ ). Evidently, it is composed of two isospins,  $I = 0$  and  $I = 1$ , with equal intensity. This may explain why the decays of  $X(3872)$  to  $J/\psi\rho$  and  $J/\psi\omega$  have near the same branchings, if these decays go mainly through rescattering of  $D$ -mesons. On the other side, radiative decays to charmonium states could be mainly determined by the  $\bar{c}c$  component. Thus, accurate studies of the resonance decays may reveal presence of several essential Fock components and separate their contributions.

As another example, let us consider a particular  $Z$ -state,  $Z^\pm(4430)$  with  $J^P = 1^+$ , observed in decays to  $\psi'\pi^\pm$  (experimental information on this state is briefly reviewed in Ref.[4]). It has mass about 4480 MeV and width about 200 MeV [4, 10]. Evidently, its main decays should be governed by strong interactions. Most probably, they conserve isospin and, therefore,  $G$ -parity. If so, then the  $Z^\pm(4430)$  has  $I^G J^P = 1^+ 1^+$ .

If widths of both initial and final mesons are taken into account, then the  $Z(4430)$  overlaps the threshold of  $D_0^*(0^+)\bar{D}_1(1^+)$  (or charge conjugate) [3]. One may expect that these final states are related with the higher Fock component of the  $Z(4430)$ ; then they will provide more intensive modes in decays of  $Z(4430)$  than  $\psi'\pi$  (though more difficult for observation). It would be important to search for this decay by detailed studying the produced system  $D\bar{D}3\pi$ .

In terms of quark content, both  $\psi'\pi^+$  and  $(D_0^*(0^+)\bar{D}_1(1^+))^+$  provide evidence for the tetraquark Fock component  $c\bar{c}u\bar{d}$  in  $Z(4430)^+$ . If this meson contains also a canonical quark-antiquark component, it should be  $u\bar{d}$ . Such component may develop decays of  $Z(4430)$  without any charm, with final states (m.b., through cascade stages) of pure pion systems. Positive  $G$ -parity means that there should be an even number of final pions. The lightest meson with  $I^G J^P = 1^+ 1^+$ ,

$b_1(1235)$ , has mass about 1230 MeV, width about 140 MeV, and decays mainly to  $\omega\pi \rightarrow 4\pi$  [3]. Having the heavier mass,  $Z(4430)^+$ , most probably, produces  $\geq 6$  pions, at least one of which should be neutral. It seems to be very difficult to search for such heavy resonance in such multipion system (note, in particular, enormous combinatorial background). This was not even attempted up to now. However, it is worth to do, since detection of the pure pion decays would clarify the nature of  $Z(4430)$ , as well as other  $X, Y, Z$  mesons.

## 8. Conclusions

Canonical picture of mesons as quark-antiquark systems is not self-consistent in relativistic theories. It can (and seems to) be, nevertheless, a good approximation for light mesons, after appropriate adjustment of parameters for the corresponding models. The above discussion suggests that the situation changes for heavier mesons, where one or more higher components of a Fock column should be accounted for. It is especially so, if the Breit-Wigner peak of the meson (or baryon as well) resonance overlaps a threshold of pair of lighter hadrons. Then the higher Fock component(s), with multi-quark content, may be most readily presented as a near-threshold hadron pair in the  $S$ -wave state. Such a picture opens a new possible direction to investigate the mysterious set of mesons  $X, Y, Z$ , different from tetraquark or molecular approaches, popular in the literature. Accurate (though difficult) experimental study of their various decay modes can allow to separate various Fock components. To demonstrate existence of a genuine tetraquark (without a  $q\bar{q}$  component) one should find a meson with non-canonical flavor quantum numbers, forbidden for a quark-antiquark configuration, either appended by gluon(s) or not.

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